0724

THREE DIMENSIONAL ATTENUATION STRUCTURE AND SITE AMPLIFICATION INVERSION BY USING A LARGE QUANTITY OF SISIMIC STRONG MOTION RECORDS IN JAPAN

Ryoichi NAKAMURA[1] And Tomiichi UETAKE[2]

SUMMARY

Inhomogeneity of attenuation structure of deep underground affect to ground motion especially in the subduction zone. Consequently, seismic intensity distributions are distorted and formed phenomenon of region of anomalous seismic intensity. Therefore, the importance of three-dimensional attenuation structure motion has attracted a growing interest to predict ground motion. Recently, a lot of acceleration seismograph, JMA87type and the Kyoshin-Net (K-NET) seismometer, were deployed widely in Japan. In this study, three dimensional attenuation structure and site amplification factor has been obtained as spectrum domain using these acceleration data. The results of the attenuation structure show that the Pacific sea plate slab is high-Q , which is consistent with other geophysical knowledge and the results of the inversion using seismic intensity data, and Q value tends to depend on frequency with proportion to about $f^{0.75}$. On the other hand, to obtained site amplification, we classified the stations of seismometer into 5 groups by ground condition mainly using S-wave logging data, and obtained amplification factor in each group by inversion simultaneously with three dimensional attenuation tomography. The results show that the frequency of large amplification obtained by inversion good agree with the predominant frequency by using S-wave velocity.

INTRODUCTION

The purpose of this study is to make clear three dimensional (3-D) attenuation structure and effect of the attenuation structure on ground motion in frequency domain. Also, site amplification effects also strongly have influence on ground motion. Hence, we intend to formulate simultaneous inversion method for both the 3-D attenuation structure and the site amplification factor. Although, the site factor and the attenuation structure effect of upper most layer contaminated each other, we classified the sites to groups by ground condition to be able to detect the site factor reasonably.

The inversion used in this study also called tomography, and its principle is as same as CT-scan used in medical science for imaging the internal organs, and has applied to geophysical science and has clarified seismic velocity and attenuation anomaly. The inversion method used in this study is ARTB method which was developed by Herman[1980] and applied to large scale geophysical problems by Hirahara[1988] because of unnecessity of resolving inverse matrix. Therefore, Nakamura et al.[1994] obtained the 3-D attenuation structure beneath the whole area of Japanese islands by using seismic intensity data according to formulation by Hashida and Shimazaki[1984]. Here, Hashida developed his work not only to Japan but also to the Aegean region [Hashida et al.,1988] and New Zealand [Satake and Hashida,1989].

[1] *Tokyo Electric Power Services Co., Ltd., 2-1-4, Uchisaiwai-cho, Chiyoda-ku, Tokyo, JAPAN, Email: naka@tepsco.co.jp*
[2] *Tokyo Electric Power Company, 4-1, Egasaki-cho, Tsurumi-ku, Yokohama, JAPAN Email: T0666057@pmail.tepco.co.jp*

METHOD

Data

The data used in this study are the strong motion records opened by Japan Meteorological Agency (the 87-type seismometer records) and the Science and Technology Agency (the K-NET seismometer). The JMA87-type and the K-NET seismometers has been observed since 1987 and 1996 respectively. The JMA87-type system is consisted of 78 stations and the K-NET system is consisted of about 1000 [Kinoshita,1998]. From these data, we could used 15768 observational data for the inversion. The total number of data N and the term of observation we used are shown in Table.1 and the epicentral distribution of earthquakes are shown in Fig.1.

We classified the stations into 5 groups. The group 1 - 4 are classified as Table 3 by the predominant period *Tg* of ground conditions of the K-NET stations which calculated by the function as

$$Tg = 4\sum_{i=1}^{n}(Hi / Vsi), \tag{1}$$

where, *Hi* and *Vsi* are thickness(m) and S wave velocity(m/s) of *i*-th layer respectively. Here, we regard the basement as *Vsi* > 300m/s. The last group5 is classified as the JMA87 stations. The distribution of these stations is shown in Fig.2.

Table 1: Data used in this study

TYPE	TERM	COMPONENT	No.
JMA87	Aug.88-Aug.93	NS	4062
K-NET	May.96-Apr.98	NS	11706

Table 2: Classification of ground condition in this study

GROUP	*Tg*(s)	Frequency(Hz)
1	- 0.2	- 5.00
2	0.2 - 0.4	5.00 - 2.50
3	0.4 - 0.6	2.5 0 - 1.67
4	0.6 -	1.67 -
5	JMA87	

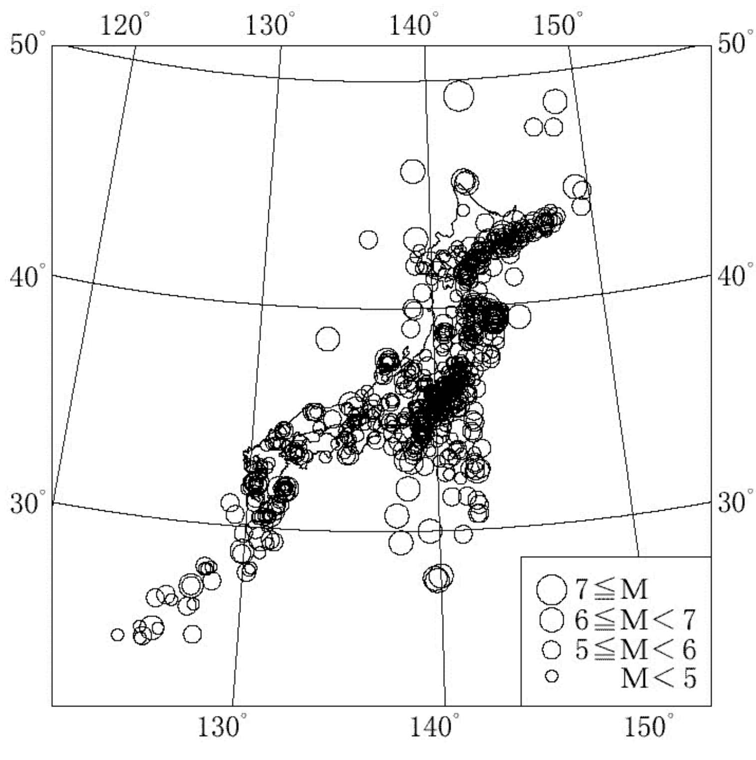


Figure 1: Epicentral distribution of earthquakes used in this study

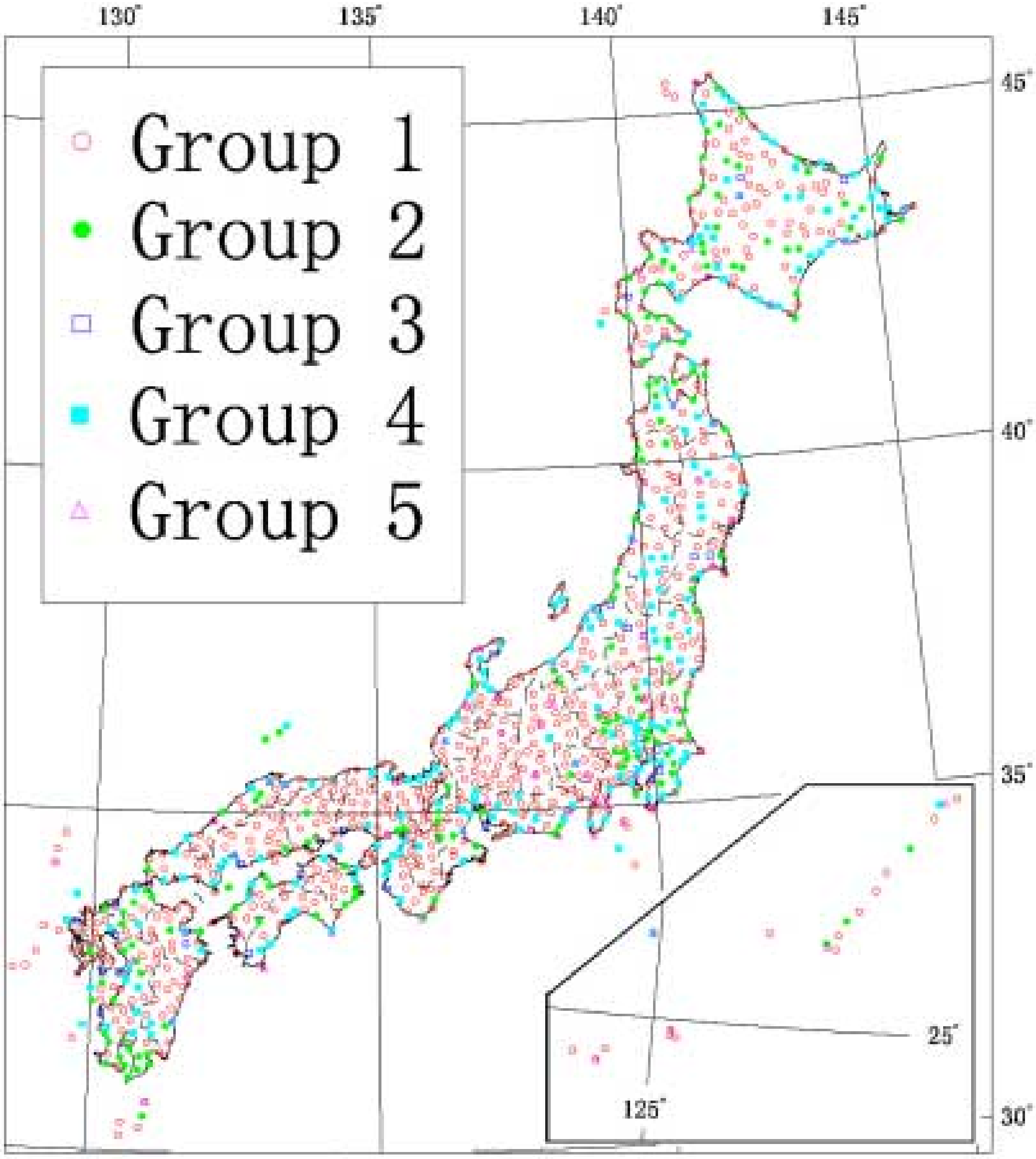


figure 2: Observational stations

Formulation

We used the formulation of inversion to estimate 3-D attenuation structure, mainly according to Hashida and Shimazaki [1984] and added it unknown parameters of site amplification as follows,

$$\alpha_{IJ}^{O} = Sa_J \cdot G \cdot g_L \cdot \exp\{-\pi \cdot f \cdot \sum (T_K / Q_K)\}, \tag{2}$$

where $\alpha^{O}{}_{IJ}$ is the observed ground acceleration spectrum, Sa_J is the source acceleration spectrum, G is the divergence factor due to geometrical spreading, g_L is the site ground amplification factor of l-th group, Q_K is the quality factor of the k-th block, and T_K is the time spent in block k. The whole study region is divided into rectangular blocks and the attenuation is assumed to be constant in each of them and the Σ is made over all blocks penetrated by the ray from j-th earthquake to i-th station (Fig.3).

To obtain unknown parameters, Sa_J, Q_K, and g_L, this formulation is rewrote to linearized observational equation.

Firstly, we give the initial values of the site amplification factor g_{OL}, the quality factor Q_{OK}, and the source acceleration spectrum Sa_{OJ} then calculate the ground acceleration spectrum α^{C}_{IJ} of the j-th earthquake and the i-th station as.

$$\alpha^{C}_{IJ} = Sa_{,nJ} \cdot G \cdot g_{OL} \cdot \exp\left\{-\pi \cdot f \cdot \sum \left(T_K / Q_{,nK}\right)\right\}. \qquad (3)$$

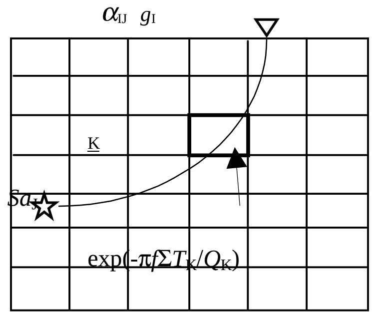


Figure 3: Scheme of this study

Secondary, we obtain the difference of natural logarithm between the calculated ground acceleration spectrum α^{C}_{IJ} and the observational ground acceleration spectrum α^{O}_{IJ} as,

$$\ln\left(\alpha^{O}_{IJ} / \alpha^{C}_{IJ}\right) = \ln\left(Sa_J / Sa_{OJ}\right) + \ln(g_L / g_{OL}) - \pi f \sum \left\{\left(Q_K^{-1} - Q_{OK}^{-1}\right) \cdot T_K\right\}, \qquad (4)$$

Thirdly, we rewrite the ground acceleration ratio, the site amplification factor ratio, the source spectrum and the quality factor difference to r_{ij}, s_j, ψ_L and δq_K^{-1} as follows,

$$r_{IJ} = \ln\left(\alpha^{O}_{IJ} / \alpha^{C}_{IJ}\right), \qquad (5)$$

$$s_J = \ln(Sa_J / Sa_{OJ}), \qquad (6)$$

$$\psi_L = \ln(g_L / g_{OL}), \qquad (7)$$

$$\delta q_K^{-1} = Q_K^{-1} - Q_{OK}^{-1}. \qquad (8)$$

Lastly, we write the whole set of acceleration residuals as a column vector $\boldsymbol{d}$, the whole set of unknown parameters as $\boldsymbol{m}$, and the linerized observational equation as $\boldsymbol{d}=\mathbf{G}\boldsymbol{m}$. The components of these vectors are as follows;

$$\boldsymbol{d}^{T} = [r_{11}, r_{21}, \ldots, r_{N1}, r_{12}, \ldots, r_{N2}, \ldots, r_{NM}], \qquad (9)$$

$$\boldsymbol{m}^{T} = [s_1, \ldots, s_M, \psi_1, \ldots \psi_L, \ldots, \delta q_1^{-1}, \ldots, \delta q_K^{-1}], \qquad (10)$$

$$\mathbf{G} = \left[\begin{array}{cccccccccccc}
1 & & & & 1 & 0 & 0 & -\pi f T^{1}_{11} & \cdot & \cdots & \cdot & -\pi f T^{K}_{11} \\
1 & & & & 0 & 1 & 0 & \cdot & & & & \cdot \\
\cdot & & & & 1 & 0 & 0 & \cdot & & & & \cdot \\
1 & & & & 0 & 0 & 1 & \cdot & & & & \cdot \\
 & 1 & & & 0 & 1 & 0 & \cdot & & & & \cdot \\
 & 1 & & & 1 & 0 & 0 & \cdot & & & & \cdot \\
 & \cdot & & & 0 & 0 & 1 & \cdot & & & & \cdot \\
 & \cdot & & & & \vdots & & \vdots & & & & \vdots \\
 & & 1 & & & \vdots & & \vdots & & & & \vdots \\
 & & \vdots & & & \vdots & & \vdots & & & & \vdots \\
 & & & 1 & & \cdot & & -\pi f T^{1}_{NM} & \cdot & \cdots & \cdot & -\pi f T^{K}_{NM}
\end{array}\right] \qquad (11)$$

INVERSION

The ARTB solution of observational equation $\boldsymbol{d}=\mathbf{G}\boldsymbol{m}$ is solved by minimizing the following quantity [Herman,1980, Hirahara,1988],

$$(\boldsymbol{d}-\mathbf{G}\boldsymbol{m})^{T}\, \mathbf{C_d}^{-1}(\boldsymbol{d}-\mathbf{G}\boldsymbol{m}) + (\boldsymbol{m}-\boldsymbol{m_o})^{T}\, \mathbf{C_m}^{-1}(\boldsymbol{m}-\boldsymbol{m_o}), \qquad (12)$$

where $\mathbf{C_d}$ and $\mathbf{C_m}$ indicate the a priori estimated covariance matrices of data and of model parameters, and $\boldsymbol{m_o}$ is the estimated initial model vector. It is assumed $\mathbf{C_d}$ and $\mathbf{C_m}$ have the following forms,

$\mathbf{C_d}=\sigma^2_d\mathbf{I}$, (13)

$$\mathrm{Cm} = \begin{bmatrix} \sigma^2_{m1} & & & & 0 \\ & \cdot & & & \\ & & \sigma^2_{mi} & & \\ & & & \cdot & \\ 0 & & & & \sigma^2_{mm} \end{bmatrix} \quad (14)$$

where σ_d^2 andσ_{mi}^2 are a priori estimates of the covariance of $\boldsymbol{d}$ and the i-th component of $\boldsymbol{m}$, respectively. Then the solution of the above equation is written as,

$\boldsymbol{m}\text{-}\boldsymbol{m_o} = \mathbf{G}^{-g}(\boldsymbol{d}\text{-}\mathbf{G}\boldsymbol{m_o})$, (15)
where
$\mathbf{G}^{-g}=(\mathbf{G}^{T}\,\mathbf{C_d}^{-1}\mathbf{G} + \mathbf{C_m}^{-1})^{-1}\mathbf{G}^{T}\,\mathbf{C_d}^{-1}$. (16)

The value of the component of $\mathbf{C_d}$ and **Cm** are assumed mainly according to Nakamura et al.[1994] for inversion parameters as σ_{DATA}=0.34, σ_{SOURCE}= 1.0 and σ_{MEDIUM} =0.01, respectively. Relaxation parameter of ARTB is adopted λ=0.1.

The region of the earth concerned here ranging from 124° to 150°E in longitude, from 23°to 50°in latitude, and from 0 to 600km in depth into blocks with a size of 0.5°x 0.5°x 30km. The total number of blocks is 56160. The ray path from the source to the station is calculated with the spherically layered earth model. We adopt the S-wave velocity model proposed by Ichikawa and Mochizuki[1971].

Concerning with equation (2) and (3), for the observed acceleration spectra α^o_{IJ} ,we use the fourier spectrum amplitude from 1Hz to 10Hz with step of every 1Hz : For example, 5Hz, we take an average of the amplitude from 5.5 to 6.5Hz. For initial value of source acceleration spectra Sa_{OJ}, we use function of Boore[1983] as follows,

$$Sa(f) = \frac{MoR(\theta,\phi)PF}{4\pi\rho\beta^3} S(f)P(f) \;, \quad (17)$$

where Mo is the seismic moment, $R(\theta,\varphi)$ is the radiation pattern(taken as 0.63), PF is the reduction factor that accounts for the partitioning of energy into two horizontal component (taken as 0.71), ρ is the density [taken as 2.7g/cc], β is shear velocity(taken as 3.2km/s), and $S(f)$, $P(f)$ are given by
$S(f)=4\pi^2 f^2/(1+(f/fc)^2)$, where $fc = 4.9 \times 10^6 \beta(\Delta\sigma/Mo)^{1/3}$ (taken as $\Delta\sigma$=100bar) , (18)
$P(f) = (1+(f/fmax)^n)$ (taken as n=3.5 and $fmax$=13Hz). (19)

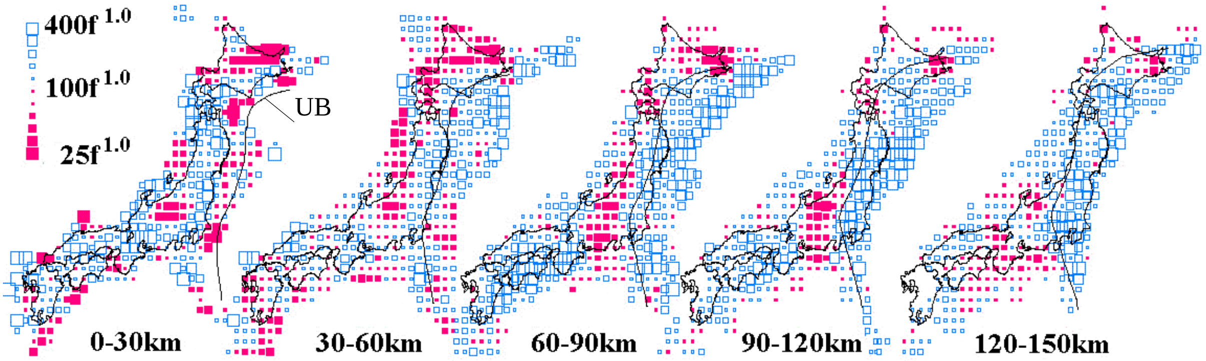
The seismic moment Mo (dyne cm) is obtained from JMA magnitude(M_J) proposed by Takemura[1990] as follows,
log Mo = 1.17M_J+ 17.72 inland, (20)
log Mo = 1.5(M_J+0.2) + 16.2 (M>=6.9), (21)
log Mo = 2.25M_J+ 11.3 (M6.2-6.9), subduction (22)
log Mo = 1.5(M_J-0.2) + 16.2 (M<=6.2). (23)

Concerning also with equation (2) and (3), the geometrical spreading factor G is equal to the inverse of the distance along the ray path. The initial value of the site amplification factor and the quality factor are given as g_{OL} =3 and Q_{OK} =100f$^{1.0}$, respectively.
The number of blocks hit by rays is 6010 and the total number of the model parameter is 6880. We use the results after the global 250th iteration of ARTB. Here, the method contains no constraint on the value of the quality factor. Therefore we simply replace any negative value with a large positive value for Q_K once in fifty global iterations. We apply a spatial smoothing filter to the obtained results of Q_K to get a stable solution; we take a moving average of neighboring seven blocks with equal weight (1/7) for the central and six neighboring blocks.

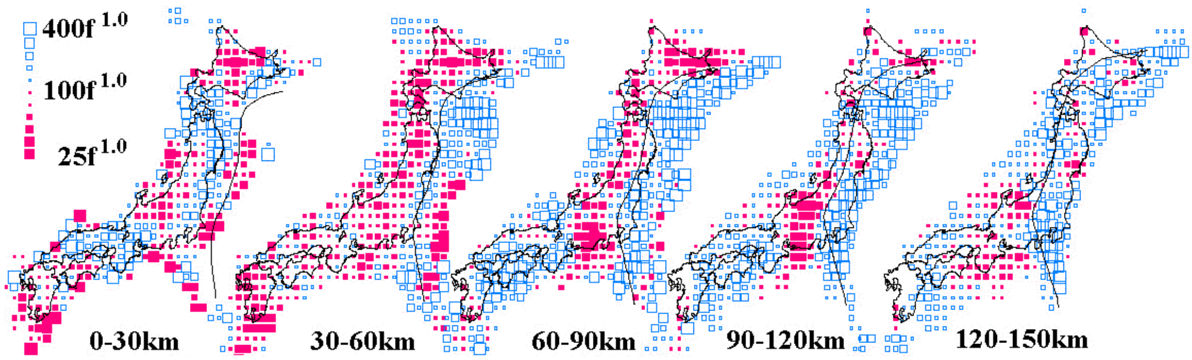
RESULTS AND DISCUSSION

Attenuation structure

Fig. 4 shows the obtained attenuation structures of 3Hz and 7Hz. The size of symbols of this figure means deviation from the level of the initial value of Q (=100f $^{1.0}$), and the open and solid rectangular are higher and lower than it, respectively. The upper boundary of the Pacific plate [Hagiwara,1986] is also shown as UB. In this figure, the Pacific plate tend to show high Q. The results of other frequency are also same tendency. These tendency is the same as the result by using seismic intensity data [Hashida,1987, Nakamura et al.,1994] . The studies of 3-D velocity structure showed consistent feature: The Pacific plate tend to high V [Kamiya,1991, Zhao,1990, etc.].



(a) 3Hz



(b) 7Hz

Figure 4: Distribution of Qs value for each layer (3Hz,7Hz). UB : the upper boundary of the Pacific plate.

The Q value second layer(30-60km) at 1,3,5,7 and 9Hz are shown in Fig. 5. This figure shows that the Q values tend to be smaller than the initial value of Q (=100f $^{1.0}$) in higher frequency, and larger in low frequency. This tendency means that the power n of f ^{n}, Q-value dependency on frequency , is smaller than 1.0. Therefore, we changed the size of symbol to depend on deviation from the Q value of 150f$^{0.75,}$ instead of 100f$^{1.0}$, shown in Fig.6. From this, we can see that Q-value tend to be proportion to about f$^{0.75}$.

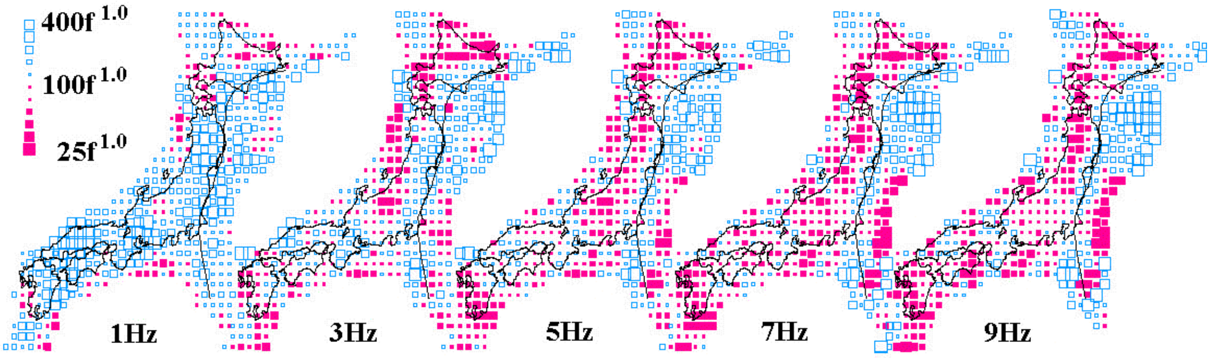


Figure 5: Q value of 1,3,5,7 and 9Hz obtained by inversion of second layer(30-60km)

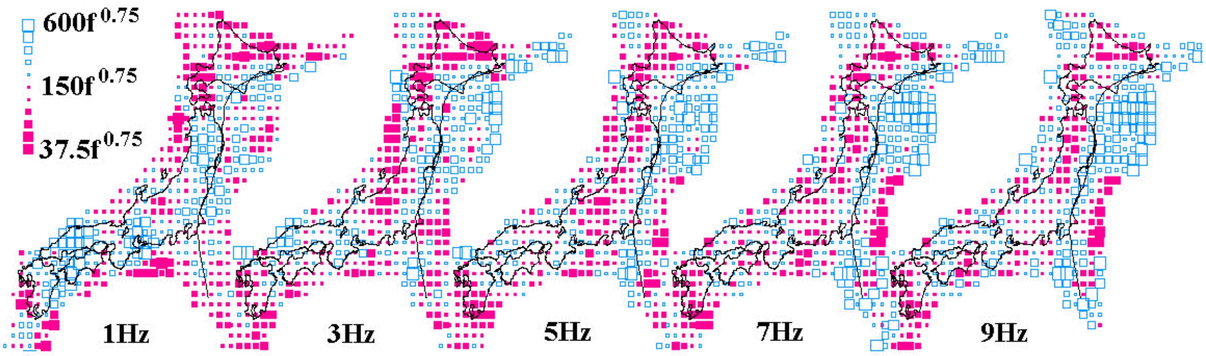


Figure 6: Q value of 1,3,5,7 and 9Hz rewrote Fig.5 by expression of 150f$^{0.75}$

Site amplification

The amplification factor from basement incident motion(Eo) to surface ground motion(2E) obtained by the inversion is shown in Fig.7. The incident motion level correspond to the level of Vs=3.2km/s , because we assumed the source spectrum on this velocity in this study as mentioned before.

The amplifications obtained in each 5 groups (Table 2). The K-NET stations are classified into the group 1 – 4 by predominant frequency. Here, the predominant frequency are given by the equation (1) by using S-wave velocity data. The JMA 87 stations are classified into the group 5.

The group 1, hard ground, have larger amplification in high frequency. This is consistent with the predominant frequency calculated by S-wave velocity. Though, no clear peak exist in this groups, it is consider that the band of predominant frequency is wide and many peaks of each amplification are averaged. The group 2 have a peak at 3-4Hz, and the group 3 , soft ground, have a peak clearly at 2Hz. These peaks coincide with the predominant frequency. Besides, in□the group 4, the amplification is larger in low frequency, and this is also consistent with the predominant frequency. These good agreement of the frequency obtained by inversion with the predominant frequency by using S-wave velocity assure us that the ground amplification factor could be able to detect by this inversion analysis.

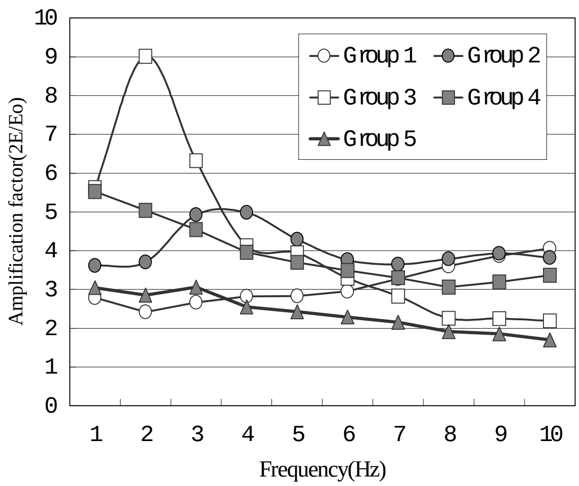


Figure7: Site amplification obtained by inversion

CONCLUSION

Seismic ground motion is affected not only by the site condition but also by the attenuation structure. This study described the method of simultaneous inversion of the three dimensional attenuation structure and the site amplification factor by using a large quantity of seismic strong motion records.

The results of the attenuation structure show that the Pacific sea plate slab is high-Q , which is consistent with other geophysical knowledge and the results of the inversion using seismic intensity data, and Q value tends to depend on frequency with proportion to about $f^{0.75}$. The results of site effect show that the frequency of large amplification obtained by inversion good agree with the predominant frequency by using S-wave velocity. Consequently, we concluded that the attenuation structure and the site effect could be detected by inversion.

ACKNOWLEGEMENT

We are grateful to Prof. Kunihiko Shimazaki, Prof. emeritus Hiroyoshi Kobayashi and Prof. Saburo Midorikawa for discussing the results of the site amplitude factor and the attenuation structure, and to Mr. Masaharu Sugahara for technical support. We wish to express our deepest thanks Dr. Shigeo Kinoshita and the persons concerned with the observational systems of the K-NET and the JMA87 seismometers.

REFERENCES

Boore, D.M. (1983) “Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra”, 73, pp1865-1894.

Hagiwara,Y.(1986) “Effects of the Pacific and Philippine-Sea plates on the gravity field in central Japan”, *J. Geod. Soc. Japan*, 32, pp12-22.

Hashida,T and Shimazaki,K (1984) “Determination of seismic attenuation structure and source strength by inversion of seismic intensity data: Method and numerical experiment”, *J. Phys. Earth*., 32, pp299-316.

Hashida, T.(1987) “Determination of three-dimensional attenuation structure and source acceleration by inversion of seismic intensity data: Japanese islands”, *Bull. Earthq. Res. Inst., Univ. Tokyo*, 62, pp247-287.

Hashida, T., Stavrakakis, G. and Shimazaki, K (1988) “Three-dimensional seismic attenuation structure beneath the Aegean region and its tectonic implication”, *Tectonophysics*, 145, p.43-54.

Herman, G.T. (1980) “Image reconstruction from projections: The fundamentals of computerized tomography”, *Academic Press, New York*.

Hirahara, K., (1988) “Detection of three-dimensional velocity anisotropy”, *Phys. Earth Planet. Interiors*, 51, pp71-85.

Ichikawa, M. and Mochizuki, E. (1971) “Travel time tables for local earthquakes in and near Japan”, Papers in Meteor. Geophys., 22, pp229-290

Kamiya,S.(1991) Three-dimensional P-wave velocity structure beneath the Japanese islands estimated from the seismological bulletin of the Japan Meteorological Agency, *J. Seism. Soc. Japan*, 44, pp185-201.

Kinoshita, S.(1998) “Kyoshin Net (K-NET)”, *Seism. Res. Let., 69*, pp309-332

Nakamura,R., Shimazaki,K. and Hashida,T. (1994) “3-D attenuation structure beneath the Japanese Islands by tomographic inversion of seismic intensity data and predicting JMA seismic intensity distributions in a broad area”, *J. Seism. Soc. Japan*, 47, pp21-32.

Satake, K. and Hashida, T. (1989) “Three-dimensional attenuation structure beneath north island, New Zealand”, *Tectonophysics*, 159, p.181-194.

Takemura, M.(1990) “Magnitude-seismic moment relations for the shallow earthquakes in and around Japan”, *J. Seism. Soc. Japan*, 43, pp257-265.

Zhao, D., Horiuchi, S. and Hasegawa, A. (1990) “3-D seismic velocity structure of the crust and upper most mantle in the northeastern Japan arc, *Tectonophysics*, 181, pp135-149.